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Modulation and Demodulation of OFDM Signals

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TECHNICAL FIELD

The present invention is related to a method and device for modulation and for demodulation of OFDM signals.

BACKGROUND OF THE INVENTION

Orthogonal frequency-division multiplexing (OFDM) has become an attractive signaling scheme for high-speed, broadband communication systems. In OFDM based systems, the user data stream is split into parallel streams of reduced rate. Each obtained substream then modulates a separate sub-carrier. By appropriately choosing the frequency spacing between the sub-carriers, the carriers are made orthogonal and some spectral overlap between the sub-carriers is permitted, leading to a high spectral efficiency. Recent wireless standards like IEEE 802.11 a/g, ETSI Hiperlan/2 and ETSI DAB/DVB-T apply OFDM to combat multipath fading with a moderate receiver complexity, while wired standards such as ANSI xDSL exploit OFDM's potential for dynamic bit-allocation and power-control on individual sub-carriers.

A typical implementation of the OFDM-related part of an IEEE 802.11a-compliant transmitter comprises a modulation mapping unit, an inverse fast Fourier transform (IFFT) unit and a parallel-to-serial unit. Incoming data bits are encoded and mapped on 48 data sub-carriers out of N=64 sub-carriers using either phase-shift keying (BPSK, QPSK) or quadrature-amplitude-modulation (16-QAM, 64-QAM). The complex baseband (BB) OFDM signal comprises an in-phase (I) and a quadrature (Q) component and is generated by a 64-point inverse discrete Fourier transform (IDFT), implemented as an inverse fast

Fourier transform (IFFT) with subsequent cyclic prefix extension and parallel-to-serial conversion in the parallel-to-serial unit. For example, a common OFDM modulator is known from US 6,304,611 B1.

After the digital-to-analogue conversion (DAC) of the obtained complex BB OFDM signal and low-pass filtering, an analogue I/Q modulator, which is driven by a carrier signal provided by an oscillator, generates the OFDM bandpass signal. After analogue filtering and amplification, the signal is transmitted in the radio frequency (RF) band over the air. Optionally, an additional mixing stage from an intermediate frequency (IF) band to the RF band is applied in heterodyne radio frontends.

Alternative implementations move the DAC to an IF band and use a digital I/Q modulator. This approach avoids amplitude, phase and delay imbalances due to filter and clock phase imperfections in the analogue I/Q modulation branches but increases the required sampling frequency. The additional digital interpolation filters can either be realized as finite impulse response (FIR) filters or be included into a larger IFFT unit by increasing the number of (unused) sub-carriers.

An OFDM receiver reverses the operation of the transmitter. Again, either an analogue or digital I/Q demodulation is feasible. In addition, pre-FFT synchronisation algorithms are used at the receiver side to estimate and adjust the correct gain setting of a variable gain amplifier (VGA) in the radio frontend, the frequency offset between transmit and receive clocks and the OFDM symbol timing.

One disadvantage of the analogue I/Q modulation and demodulation is that two analogue branches are required for the processing of the analogue complex baseband signals. This

requires analogue components which can lead to an imbalance between the in-phase and the quadrature components. The estimation and compensation of the I/Q imbalance is expensive and leads to a gap between practical performance and theoretical performance.

The disadvantages of the digital I/Q modulation are that the sampling rate is higher than by an analogue I/Q modulation and that the complexity of the digital parts of the mixing stage is increased.

It is an object of the present invention to provide a new method for modulating and demodulating of OFDM signals, thereby avoiding the disadvantages indicated above. It is a further object of the present invention to provide devices for modulation and demodulation of OFDM signals.

SUMMARY OF THE INVENTION

The disadvantages are overcome by the methods for modulating and demodulating as well as by the devices for modulation and for demodulation of OFDM signals. Preferred embodiments of the present invention are indicated in the dependant claims.

According to a first aspect of the present invention, a method for modulating sub-carrier symbols to an intermediate-frequency OFDM signal having even and odd samples is provided. Firstly, a number N of sub-carrier symbols is transformed to pre-processed sub-carrier symbols. A complex inverse discrete Fourier transform (IDFT) on the pre-processed sub-carrier symbols is then performed to generate complex output symbol. The complex output symbols are then transformed to the intermediate-frequency OFDM signal. The sub-carrier symbols are transformed so that the even and odd samples of the

intermediate-frequency OFDM signal are given by the real and imaginary parts of the complex output symbols.

One idea of the present invention lies in the pre-processing of the sub-carrier symbols in a way that the inverse discrete Fourier transform, also referred to as transformation, generates output symbols wherein the real as well as the imaginary part can be interpreted as a series of real samples of the intermediate-frequency OFDM signal. Thereby, the disadvantages caused by imbalance between the in-phase and the quadrature component of the complex output symbol while transforming them to the intermediate-frequency OFDM signal can be avoided. The pre-processing of the sub-carrier symbols is performed in a manner that complex output symbols are generated by the IDFT as known from the prior art but wherein the real and imaginary parts of the complex output symbols are multiplexed to real samples of the intermediate-frequency OFDM signal.

Preferably, the transforming of the sub-carrier symbols to pre-processed sub-carrier symbols is performed according to the following function:

$$Z(k) = \frac{1}{2} \cdot \left[F(k) + F(N-k)^{*}\right] + \frac{1}{2} \cdot j \cdot \left[F(k) - F(N-k)^{*}\right] \cdot e^{+j\pi k/N}$$

wherein F(k) are sub-carrier symbols and Z(k) are pre-processed sub-carrier symbols for k=0…N-1. This function is the preferred function to perform the pre-processing of the sub-carrier symbols and allows obtaining the intermediate-frequency OFDM signal as desired according to the present invention.

It can be provided that the complex inverse discrete Fourier transformation is usually performed as an inverse fast Fourier transformation which is commonly known and which is to be preferred because the processing can be performed efficiently.

Preferably, the modulation of the sub-carrier symbols to the intermediate-frequency OFDM signal includes that the sub-carrier symbols are assigned to a spectrum $F(i)$ with $i=0\ldots 2N-1$ of the real valued intermediate-frequency OFDM signal $f(n)$ with $n=0\ldots 2N-1$, wherein the negative frequency contents can be derived from the symmetry property spectra of real sequences, $F(i) = F(2N-i)^{*}$. Furthermore, the spectrum $F(k)$, with $k=0\ldots N-1$ is converted to pre-processed complex sub-carrier symbols $Z(k)$ using the symmetry property of spectra of real sequences, wherein $Z(k) = X(k) + j \cdot Y(k)$, with $X(k)$ and $Y(k)$ defining the spectra of real sequences $x(n)$ and $y(n)$. The inverse discrete Fourier transformation transforms the pre-processed complex sub-carrier symbols $Z(k)$ into the complex output symbols $z(n)=x(n)+ j \cdot y(n)$. Preferably the transforming of the complex output symbols is performed by multiplexing the real and the imaginary parts of the complex complex output symbols to a stream of even and odd samples of the intermediate-frequency OFDM signals.

According to another aspect of the present invention, a method for demodulating an intermediate-frequency OFDM signal having even and odd samples to sub-carrier symbols is provided. The intermediate-frequency OFDM signal is transformed into complex input symbols wherein the even and odd samples are associated to the real and imaginary parts of the complex input symbols. A complex discrete Fourier transformation of the complex input symbols is performed to generate complex DFT output symbols. The complex DFT output symbols are further transformed to post-processed sub-carrier symbols.

The method for demodulating the intermediate-frequency OFDM signal provides the inverse operation related to the method for modulating as described above. The even and odd samples of an incoming intermediate-frequency OFDM signal are associated to the real and imaginary part of the complex input symbols for a discrete Fourier transformation. The results of the discrete Fourier transformation are post-processed to sub-carrier symbols.

The post-processing is preferably carried out according to the following function:

$$F(k)=\frac{1}{2}\cdot\left[Z(k)+Z(N-k)^{*}\right]-\frac{1}{2}\cdot j\cdot\left[Z(k)-Z(N-k)^{*}\right]\cdot e^{-j\pi k/N}.$$

The discrete Fourier transformation can be performed as a fast Fourier transformation.

Preferably, the demodulation of the real intermediate-frequency signal to sub-carrier symbols is performed by the following steps. First, the even and odd samples of the intermediate-frequency OFDM signal f(n) are demultiplexed onto the real and imaginary parts of the complex DFT input symbols z(n)=x(n) + j x y(n) with x(n)=f(2n), y(n)=f(2n+1), and n=0…N-1. The complex discrete Fourier transformation of the complex input symbols z(n) into complex output symbols Z(k)=X(k) + j·Y(k) with k=0…N-1 is performed wherein X(k) and Y(k) are the spectra of the real sequences x(n) and y(n). The complex output symbols Z(k) with k=1…N-1 are post-processed to the spectrum F(k)=X(k) + $e^{-j\pi\cdot\frac{k}{N}}$ Y(k) of the real valued intermediate-frequency OFDM signal f(n). The spectrum F(k)

with k=1…N-1 of the real valued IF signal f(n) is assigned to the associated sub-carrier symbols.

According to another aspect of the present invention, an orthogonal frequency-division multiplexing modulator for modulating sub-carrier symbols to an intermediate-frequency OFDM signal having even and odd samples is provided. The modulator comprises first means for transforming a number N of the sub-carrier symbols to pre-processed sub-carrier symbols. It further comprises DFT means for performing a complex inverse discrete Fourier transformation (IDFT) of the pre-processed sub-carrier symbols to generate complex output symbols. Furthermore, second means for transforming the complex output symbols to the intermediate-frequency OFDM signal is provided. The sub-carrier symbols are transformed in the means for transforming so that the even and odd samples of the intermediate-frequency OFDM signal are given by the real and imaginary parts of the complex output symbols.

Thereby, a modulator for modulating sub-carrier symbols to an intermediate-frequency OFDM signal is provided which operates according to the method of modulating according to the present invention.

Preferably, the first means for transforming include means for assigning the sub-carrier symbols to a spectrum of the real valued OFDM signal wherein the negative frequency contents can be derived from the symmetry property of spectra of real sequences. The first means for transforming further comprises means for converting the spectrum to pre-processed complex sub-carrier symbols using the symmetry property of spectra of real sequences.

According to a preferred embodiment of the present invention, the first means for transforming and the IDFT means are integrated in one device.

According to another aspect of the present invention, an orthogonal frequency-division multiplex demodulator for demodulating an intermediate-frequency OFDM signal having even and odd samples to sub-carrier symbols is provided. The demodulator includes means for transforming the intermediate-frequency OFDM signal to complex input symbols wherein the even and odd samples are associated to the real and imaginary part of the complex input symbols. Using DFT means a complex discrete Fourier transformation is performed on the complex input symbols to generate complex DFT output symbols. By means for transforming the complex DFT output symbols post-processed sub-carrier symbols are generated.

The demodulator thereby comprises means to perform the method for demodulating according to the present invention.

DESCRIPTION OF THE DRAWINGS

Embodiments of the present invention are described in more detail together with the accompanying drawings, wherein

Figure 1 shows a prior art OFDM modulator;

Figure 2 shows a OFDM modulator according to one embodiment of the present invention;

Figure 3 shows an illustration of the step of assigning the sub-carrier symbols to a spectrum of real valued intermediate-frequency OFDM signals; and

Figure 4 an OFDM demodulator according to another embodiment of the present invention.

DETAILED DESCRIPTION OF EMBODIMENTS

In Figure 1, a typical implementation of an OFDM modulator according to the prior art is depicted. The OFDM modulator comprises a modulation mapping unit 3. A stream S of incoming data bits is encoded to a number of complex symbols using phase-shift-keying (BPSK, QPSK) or quadrature-amplitude-modulation (16-QAM, 64-QAM) and mapped onto K data sub-carriers out of N sub-carriers by the modulation mapping unit 3. Additional sub-carriers can be reserved for pilot (training) tones while the DC sub-carrier is usually unused to avoid difficulties with converter offsets. The remaining sub-carriers are unused and produce spectral guard bands to reduce out-off-band interference and to relax radio-frontend filter requirements.

These so-called sub-carrier symbols are then fed into an IFFT unit 4 to perform a N point inverse discrete Fourier transformation (IDFT), thereby generating a complex baseband (BB) OFDM signal comprising an in-phase (I) and a quadrature (Q) component of complex output symbols. The inverse discrete Fourier transformation is commonly performed as a fast Fourier transformation with subsequent cyclic prefix extension. The complex output symbols are fed in a parallel-to-serial converter 5 to obtain a serial stream of complex digital baseband signals comprising real and imaginary parts I, Q.

The real and imaginary parts I, Q of the complex complex digital baseband signals are then forwarded each to a digital-to-analogue conversion unit 6 to convert the digital values to respective analogue values each of them then low pass filtered

in filter 7 and modulated in an analogue I/Q modulator 8, which is driven by a carrier signal C provided by an oscillator 9. The output of the I/Q modulator 8 generates the OFDM bandpass signal. After analogue filtering and amplification, the signal is transmitted in the radio frequency (RF) band over the air. Optionally, an additional mixing stage from an intermediate frequency (IF) band to the RF band is applied in heterodyne radio frontends.

Alternative implementations move the digital-to-analogue conversion unit to the intermediate frequency band and use a digital I/Q modulator. This approach avoids the disadvantages of amplitude, phase and delay imbalances due to filter and clock phase imperfections in the analogue I/Q modulation branches but increases the required sampling frequency. The additional digital interpolation filters can either be realized as FIR filters or be included into a larger IFFT by increasing the number of unused sub-carriers.

A common OFDM demodulator reverses the operations of the OFDM modulator. Again, either an analogue or digital I/Q demodulation is feasible. In addition, synchronization algorithms are required at the demodulator to estimate and adjust the correct gain setting of the variable gain amplifier in the radio frontend, the frequency offset between transmit and receive clocks and the OFDM symbol timing.

Figure 2 shows a preferred embodiment of an OFDM modulator according to the present invention. The OFDM modulator according to the invention substantially comprises similar parts as included in a common OFDM modulator, such as the modulation mapping unit 3 to encode and to map the incoming stream of data bits to complex sub-carrier symbols as known from prior art. Also, the IFFT unit 4 as known from the

conventional OFDM modulator is used to generate complex IDFT output symbols z(n). Same reference numbers are used to indicate the same functional blocks or units. As the setup for modulation and demodulation is approximately symmetrical, the corresponding formula signs within the specification are chosen to be identical.

A second transforming means 50 comprises a parallel-to-serial unit 51 and a multiplexer 52 which in order serialize the complex IDFT output symbols z(n) and multiplex the real and imaginary parts of z(n) into even and odd samples of the intermediate-frequency OFDM signal.

Between the modulation mapping unit 3 and the IFFT unit 4, a pre-processing unit 10 is introduced to perform a pre-processing of the complex sub-carrier symbols at the output of the modulation mapping unit 3 and to generate pre-processed complex sub-carrier symbols to be fed into the IFFT unit 4. The pre-processing unit 10 comprises an assigning means 10a that basically is an assign unit 10a which assigns the sub-carrier symbols to a spectrum F(i) with i=0…2N-1 of the intermediate-frequency OFDM signal. Negative frequency contents are derived from the symmetry property of spectra of real sequences, i.e. $F(i)=F(2N-i)^*$. The pre-processing unit 10 further comprises converter means 10b, i.e. a converter that converts the sub-carrier symbols to the pre-processed complex sub-carrier symbols by using the symmetry property of spectra of real sequences.

In the pre-processing unit 10, an operation according to the following procedure is performed. Given the frequency of the intermediate frequency as $f_{IF} = n\ f_C$ wherein $n > \lfloor B/(2\ f_C) \rfloor$ represents an integer value and $\lfloor \cdot \rfloor$ defines the floor operator, f_C the sub-carrier frequency separation, and B the

OFDM signal bandwidth, it is possible according to the method of the present invention to remove the digital I/Q modulation and use the IFFT unit 4 together with the pre-processing unit 10 and the parallel-to-serial unit 5a to directly generate the intermediate-frequency OFDM signal, also referred to as IF signal. This signal is also contemplated as a real valued intermediate-frequency OFDM signal.

One concept of the invention to create the real valued intermediate-frequency OFDM signal directly by using IFFT means is outlined in the following paragraph.

The spectrum shown in Figure 3a is periodic with a periodicity given by the sampling frequency f_S. An N-point-IFFT unit covering one period is used to transform the complex BB OFDM signal from the frequency to time domain. The spectrum shown in Figure 3b can be obtained without a digital I/Q modulation by, first, doubling the sampling clock frequency to $f'_S = 2f_S$, second, shifting the center frequency of the original spectrum to f_{IF}, and third, introducing components to the resulting spectrum to enforce the symmetry property as required for real sequences x(n). The output of an inverse Fourier transformation contains only real values if the spectrum on the input side includes a symmetry according to $FFT_N(x, f) = FFT_N(N-k, x)^*$.
To convert this spectrum, the size of the used IFFT unit is increased to 2N in principle.

Given that a low IF frequency is selected, i.e. $n < N-\lfloor B/(2 f_C)\rfloor$, a intermediate-frequency OFDM signal comprising 2N real values can be generated.

As shown in the following, a single N-point complex fast Fourier transform (FFT) with an additional butterfly stage can

be used to evaluate two N-point real FFTs or one 2N-point real FFT. The N point FFT of a sequence z(n) is defined as

$$Z(k) = FFT_N(k,z) = \frac{1}{\sqrt{N}}\sum_{n=0}^{N-1} z(n)e^{-j2\pi kn/N}$$

with $k = 0 \ldots N-1$. In the sequel, two symmetry properties of the FFT will be useful. For a complex (or real) sequence $z(n)$, the property

$$FFT_N(k,z^*) = FFT_N(N-k,z)^*$$

holds, while the Fourier transform of a real sequence x(n) is additionally conjugate-symmetric, i.e.

$$FFT_N(k, x) = FFT_N(N\text{-}k, x)^* \rightarrow X(k) = X(N-k)^* .$$

A single N-point complex FFT can be used to evaluate the N-point FFT of two real sequences x(n) and y(n) simultaneously. A complex sequence is defined by:

$$z(n) = x(n) + jy(n) .$$

Solving for x(n) and y(n) one gets

$$x(n) = \frac{1}{2}[z(n) + z(n)^*] ,$$

$$y(n) = -\frac{1}{2}j[z(n) - z(n)^*] .$$

Evaluating the FFT and applying the symmetry property leads to the result

$$X(k) = FFT_N(k,x) = \frac{1}{2}[FFT_N(k,z) + FFT_N(N-k,z)^*]$$

$$Y(k) = FFT_N(k,y) = -\frac{1}{2}j[FFT_N(k,z) - FFT_N(N-k,z)^*].$$

So the transforms can be easily extracted by a simple butterfly stage after the FFT.

To extend this scheme to evaluate a 2N point FFT of a real sequence f(n) using a N-point complex FFT, x(n) = f(2n) is defined as the even samples and y(n) = f(2n+1) as the odd samples and again z(n)=x(n)+jy(n). From the FFT's linearity and time-shift property

$$F(k) = FFT_{2N}(k,f) = X(k) + e^{-j\pi k/N}Y(k)$$

can be derived, which finally gives the butterfly function:

$$F(k) = \frac{1}{2}[\{Z(k) + Z(N-k)^*\} - j\{Z(k) - Z(N-k)^*\}e^{-j\pi k/N}]$$

for k=0...N–1. The remaining (redundant) values for k=N...2N–1 are determined by the symmetry property of real sequences.

Thus, a single N point complex FFT with an additional butterfly stage can be used to evaluate two N point real FFTs or one 2N point real FFT.

The pre-processing stage 10 of the OFDM modulator according to the present invention preferably carries out the following operation, which can be obtained accordingly as the inverse operation of the above butterfly function:

$$Z(k) = \frac{1}{2} \cdot \left[F(k) + F(N-k)^{*}\right] + \frac{1}{2} \cdot j \cdot \left[F(k) - F(N-k)^{*}\right] \cdot e^{+j\pi k/N},$$

wherein k=0...N-1 and F(k) is the data symbol to be modulated onto sub-carrier k.

The output of the IFFT unit 4 has real and imaginary parts wherein the real parts of the complex output symbols z(n) are interpreted as the even samples and the imaginary part as the odd samples. This can be performed by a multiplexer which is preferably included into the parallel-to-serial unit 5a. The output of the multiplexer is connected to a single digital-to-analogue converter unit 11 which directly generates the intermediate-frequency OFDM signal by using a double sampling rate.

In Figure 4, a demodulator for OFDM signals is shown. The received intermediate-frequency OFDM signal is converted by an analogue-to-digital converter unit 12 into a signal stream f(n) which is fed into a third transformer 13 which transforms the intermediate-frequency OFDM signal to complex input symbols. The third transformer 13 comprises a de-multiplexer 13a that de-multiplexes the even and odd samples of the intermediate-frequency OFDM signal onto the real and imaginary parts of the complex DFT input symbols. In other words, the third transformer 13 with the de-multiplexer 13a associate the even and odd samples with the real and imaginary part I, Q of the complex input symbols z(n). The complex input symbols are then fed to a FFT unit 14 to perform a fast Fourier transformation on the complex input symbols to obtain sub-carrier symbols Z(k).

Substantially, a fourth transformer 15 performs the post-processing of the complex DFT output symbols Z(k) to post-

processed sub-carrier symbols F(k), for example according to the function as determined above:

$$F(k)=\frac{1}{2}\cdot\left[Z(k)+Z(N-k)^{*}\right]-\frac{1}{2}\cdot j\cdot\left[Z(k)-Z(N-k)^{*}\right]\cdot e^{-j\pi k/N}$$

The fourth transformer 15 comprises a post-processing means 15a that post-processes the complex DFT output symbols Z(k) with k=1…N-1 to the spectrum F(k)= X(k)+exp(-j*pi*k/N)*Y(k) of the intermediate-frequency OFDM signal. The fourth transformer 15 further comprises an assigning means 15b that assigns the post-processed sub-carrier symbols to an order for further processing. The assigning means 15b can include a table which refers to standardized symbols.

In a demodulation-demapping unit 16, the post-processed sub-carrier symbols F(k) are serialized and decoded so that a data stream S of output bits can be achieved.

The method for modulating and demodulating according to the present invention has the advantage that any I/Q imbalances due to digital I/Q modulation or demodulation can be avoided with a reduced complexity of the units or devices. Compared to the analogue I/Q modulation approach, only a single digital-to-analogue converter unit but with a double clock rate is used. The same is true for the demodulation approach, where only a single analogue-to-digital converter unit is applied.

The IFFT unit 4 and the FFT unit 14 can be combined with an additional pre-processing stage 10 and post-processing stage 15, respectively. IFFT unit 4 and pre-processing stage 10 can be combined in a tailored IFFT operable to perform the IFFT as well as the pre-processing of the complex input symbol. In the same way, the FFT unit 14 and the post-processing stage 15 can

be combined in a tailored FFT unit which is operable to perform the FFT and the post-processing to achieve the post-processed output symbols. Tailored IFFT unit and tailored FFT unit can be designed as an integrated circuit.

The intermediate frequency f_{IF} can be chosen on a grid of N times the sub-carrier spacing f_C with $N > [B/(2f_C)]$ as an integer. This allows trading of complexity between analogue and digital filters. Oversampling architectures to relax filter requirements are possible, as well.